Testing rift versus transform models for the Guyana margin using 3D gravity model compared to seismic reflection data

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Summary:

The 700-km-wide Guyana margin of northeastern South America includes a 40-50 km thick elevated Archean greenstone belt of the Guiana shield that thins to a 26-11-km-thick necked zone of continental crust, that in turn thins to normal 9-6-km-thick oceanic crust. To the east, Suriname is partially fronted by a volcanic margin composed of Middle Jurassic volcanic flows underlying the Demerara Plateau. Despite the success of offshore Guyana and Suriname, the Jurassic tectonic origin between the Guyana-Suriname margin remains controversial with two, widely differing models for its tectonic origin: 1) the margin formed along a Jurassic transform related to the early opening of the Central Atlantic Ocean; 2) the margin formed by orthogonal rifting related to the Jurassic opening of the Central Atlantic. To test the two models, we perform a 3D gravity inversion with marine satellite gravity constrained by previous refraction surveys and a grid of 2D seismic data. Margin-perpendicular transects from the inversion exhibit a 167-74 km tapered necked zone with an average top basement gradient of 4 degrees supporting a rifted-passive origin. This thinning and wide necking zone and the location of the continent-ocean boundary has a significant impact on the heat flow across the margin.

Introduction:

The success of hydrocarbon discoveries in the deepwater Guyana-Suriname basin began with the Liza discovery in 2015 and has now reached 9 billion barrels of oil equivalent (Tomic, 2021). Our objective is to examine the fundamental tectonic origin of this prolifie hydrocarbon area.

<u>Tectonic phases affecting the Guyana-Suriname area</u>

Three tectonic phases that have affected this area include: 1) Jurassic opening of the Central Atlantic Opening that resulted in the east to west extension between North America and Africa; 2) Cretaceous oblique opening of the Equatorial Atlantic led to right-lateral transtension; 3) a passive margin phase from the Late Cretaceous to Recent. The southeastern area of the Guyana-Suriname basin includes Jurassic volcanic flows of the Demerara Plateau (Basile et al., 2020). The Demerara fracture zone separates the Cretaceous oceanic crust from thinned continental Jurassic crust of the Demerara Plateau and exhibits steep dips, basement highs, and a Moho slope of 11° that are characteristic of a transform margin (Lepinay et al., 2016). Parallel to the Guyana-Suriname margin, rifts are observed overlying the tapered upper crust and are filled with syn-rift Upper Jurassic units (Loparev et al., 2021). Lacking SDRs, the extensional faulting framework found in the upper crust and steadily declining post-rift subsidence of the Guyana-Suriname margin is characteristic of an orthogonally-rifted, magma-poor margin.

Previous plate models

Previous plate models define three possibilities for the tectonic origin of the Guyana-Suriname margin: 1) the Central Atlantic opening extends to the Guyana-Suriname transform margin adjacent to the magma-rich rifted margin of the western Demerara Plateau rifting to the northwest; 2) both the volcanic margin of the Demerara Plateau and the Guyana-Suriname rifted margin obliquely open to the north-northwest; or 3) before the extension of the Central Atlantic Opening, the Guyana-Suriname margin rifted to the northeast weakly with little magmatic input (figure 1a).

One of the key features differentiating between a transform or rifted margin is crustal thickness. In a rifted margin, a gradual thinning of continental to oceanic crust. The width of the necking domain decreases as obliquity increases along the margin. In contrast, the continent oceanic boundary (COB) is abrupt in a transform margin, with high relief in the basement, and a short truncated Moho. A regional COB can be initially interpreted through gravity filters (figure 1b). This study explores the crustal thickness of the Guyana-Suriname margin through 3D gravity inversion of the Moho correlated with a 332 by 160 km wide seismic interpretation.

Methods

<u>3D gravity inversion</u>

To complete the 3D gravity inversion, an initial isostatic Moho depth was calculated using Airy isostasy methods with a shoreline depth of 33 km and an exponential decay function for sediment density ranging from 2.15 to 2.7 g/cc based on the sediment thickness. The Total Sediment Thickness of the World's Oceans and Marginal Seas dataset was used as the basis for the exponential decay function, while SRTM 3-arc-second topography was merged with GEBCO 15 arc-second bathymetry to produce an overall topographic profile across the Guyana margin. The isostatic Moho was inverted with a water density assigned 1.03 g/cc, topographic density determined through the decay function with a sediment and basement density of 2.825 g/cc, and a Moho density of 3.3 g/cc. After this inversion, an average DC shift was applied along with constraints from 99 regional refraction controls and shifted to achieve the lowest control error. These refraction constraints had a velocity range from 7.85 to 8.5 km/s. These integrated data resulted in a constrained inversion that converged to 1 mGal with a 1 km Moho depth error in the vicinity of a refraction control.

<u>Seismic Interpretation</u>

We interpreted 8 stratigraphic horizons throughout a grid of 2D seismic data that covers the central to the western areas of the Guyana Basin (Fig. 1b). The top basement surface is characterized by multiple and elongate depressions that trend to the northeast and are characterized by areas of high to low reflectance. Overlying sub-parallel reflectors were interpreted to be overlain by Upper Jurassic platform carbonates terminated by a Callovian unconformity that marked the intiation of post-rift subsidence. In the northwestern part of the study area, folds and thrusts disrupt passive margin deposition as the result of the eastward advancing Caribbean plate (Fig. 1b).

Results

<u>Interpretation of crustal structure</u>

The Demerara transform margin of early Cretaceous age exhibits an expected 8 km truncation in the inverted Moho. However, the model's crustal thickness includes the denser SDR units throughout the inversion (Figure 1b). Seismic comparisons reveal thick SDR units of the Demerara Plateau have thicknesses up to 25 km and thin to the northwest into the Guyana-Suriname basin (Reuber et al., 2016). From the Guinea shield into the Guyana-Suriname basin, the seismic interpretation instead exhibits Jurassic extensional faults protruding the basement underlying the Aptian unconformity with a near-grade slope (Yang and Escalona, 2011). The inverted Moho and crustal structure indicate a broad zone of tapered necking over the major rift features identified in the gravity interpretation with a smooth transition to COB consistent to basement-related rifting seen in seismic (figure 2). Many of the basement faulting complexes are apparent in the inverted Moho as an artifact. This includes the northeast-oriented Nickerie and Commewijne grabens.

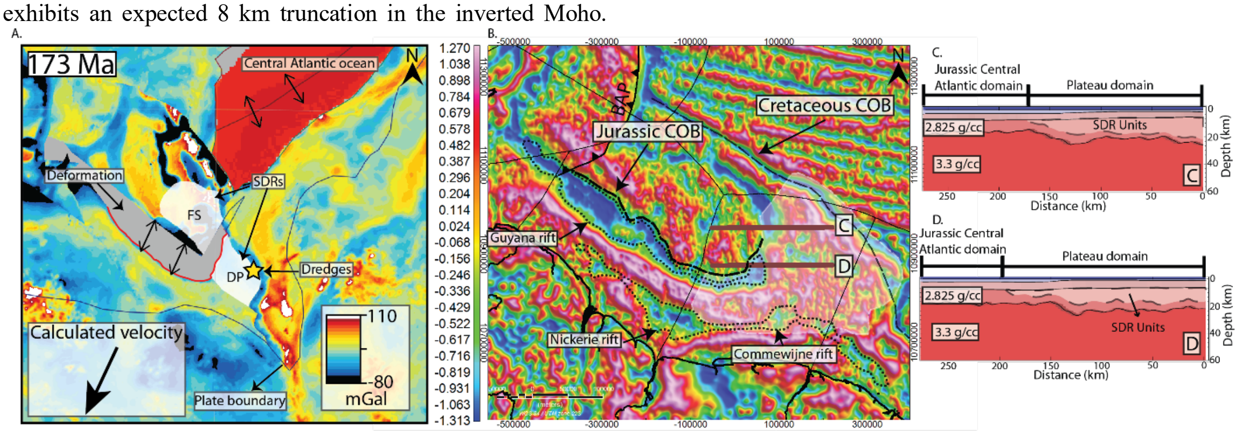

Figure 1: a) Our proposed model for orthogonal Jurassic rifting of the Guyana-Suriname basin modified from Mueller et al. (2019) shown on a basemap of free-air gravity data (Sandwell et al., 2014). Dredged samples with Jurassic radiometric ages are from Basile et al. (2020). DP = Demerara Plateau; FS = Florida Straits; SDR = Seaward dipping reflectors. b) Seaward dipping reflector (SDR) extent is shown by whitish overlay and was inferred from a tilt-angle filtered gravity with 40 km low-pass (Butterworth) filter of the free-air gravity dataset (Reuber et al., 2016; Sandwell et al., 2014). Inverted Moho comparison with 20-km-thick SDR units were integrated into the modeled crustal units (Museur et al., 2021).

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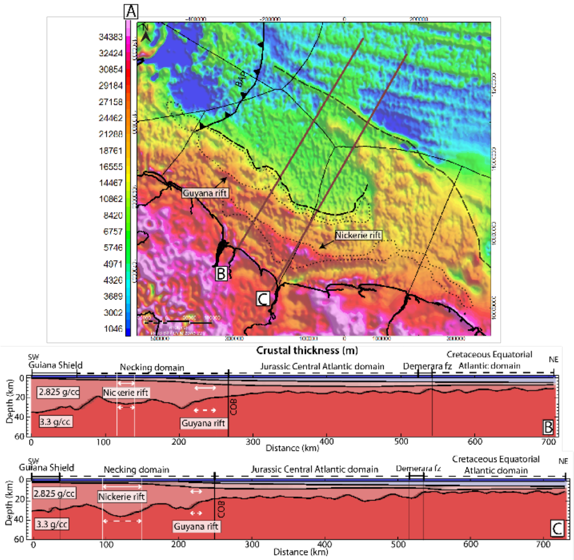

Figure 2: a) Northeast-oriented crustal thickness calculated by inverted Moho subtraction from sediment with COB defined from filtered free-air gravity (Straume et al., 2019). b) Cross-sections of the 3D model highlighting the extent of rift features and COB identified in the tilt-angle filtered free-air gravity data.

Application of this study to deepwater exploration

Our proposed model for a rifted margin in Guyana and its predicted location of the continent-ocean boundary has important implications for deepwater exploration in the Guyana Basin. On all rifted or transform margins the COB would mark an important boundary in the geothermal gradient between the relatively cold oceanic crust that lacks radiogenic heat production and the thinned continental crust that is relatively warmer and more conducive to hydrothermal maturation in the overlying sedimentary rocks as the result of radiogenic heat production from the mineral components of the basement. In the geothermal gradient with the. In their study of the Guyana margin, Lepinay et al. (2016) placed their COB related to their Jurassic transform model about 65 km seaward of the positon that we show for our COB on our map in Figure 1. For both COBs, our prediction is that the

We interpret gradual thinning of the crust toward the COB as evidence for Jurassic orthogonal northeast-directed opening Colder and thinner oceanic crust to the northeast of our proposed COB would risk deepwater exploration in this distal zone.

Conclusions

Understanding the origin of the Guyana-Suriname margin and the location of its continent-ocean boundary is fundamental for its deepwater exploration given the differential in heat flow between relatively warmer, rifted continental crust and relatively colder, oceanic crust. To better locate the continent-ocean boundary (COB) and its tectonic origin (rift vs. transform), a 3D gravity model was created with a constrained inverted Moho surface that provided insights into the overall crustal structure and geometry and the location of its COB. Key results from the inversion are summarized as follows:

1. Margin-perpendicular transects from the 3D volume show that the Guyana margin exhibits a highly tapered necked zone of thinned, continental crust with an average top basement gradient of 4 degrees over a range of 167-74 km; we see no evidence for an abrupt truncation and rapid change in crustal thickness that is a defining characteristic of a transform margin.
2. Interpretation of seismic interpretation lines reveals dipping sedimentary wedges of inferred Jurassic age up to 3 seconds in time-thickness. Margin-perpendicular transects show crustal thickening beneath the Nickerie and Commewijne grabens that we interpret as an artifact of inversion in the 3D model.
3. The seaward limit of the Guyana rifted-passive margin is abruptly truncated up to 8 km by the Demerara fracture zone formed during the Aptian transtensional opening of the Equatorial Atlantic Ocean that post-dated the rifting of the Guyana margin by at least 30 million years .

This thinning to oceanic crust may be reducing source rock temperature by 14°C along the COB due to a 3 mW/m² heat flow loss in the crust.

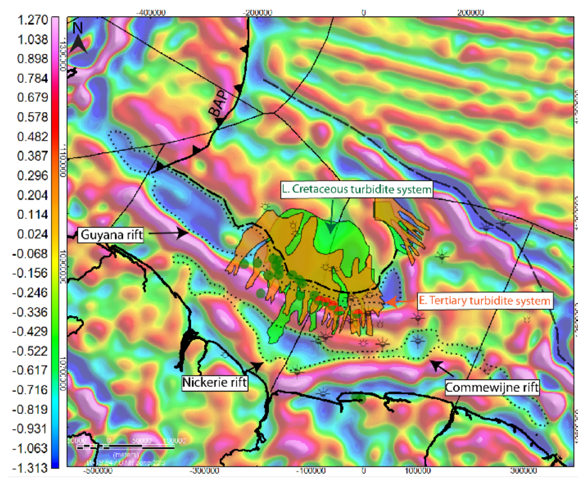

Figure 3: Productive and non-productive wells, excluding the Ranger seamount, exhibited with associated turbidite systems overlaying first vertical gravity gradient with a 40 km low-pass filter (Ballard, 2019). Rift features are defined from tilt angle filtered free-air gravity data.

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Acknowledgments

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